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TECHNICAL NOTE

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ON THE ELECTRON DENSITY DISTRIBUTION ABOVE THE F2 PEAK (REVISED)

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SUMMARY

The distribution of free electrons in a heterogeneous upper ionosphere is discussed. According to theoretical arguments as well as experimental evidence, the electron density distribution well above the F2 peak corresponds to a diffusive equilibrium distribution. It is shown that accurate electron density measurements in this altitude region allow the determination of associated atmospheric parameters such as scale height and temperature, as well as the nature and concentration of the light ions, since within this altitude region a transition occurs from the predominant heavy ion (O^+) to the light ions (H^+ and/or He^+).

The previous release of this report bore the same title but was identified as Technical Note D-1065.

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INTRODUCTION

The exploration of the ionsophere above the F2 peak has been made possible only in recent years, by the advent of rockets and satellites and of the ground-based incoherent backscatter technique. One of the basic quantities measured in these experiments is the electron density. At present only a limited number of electron density profiles have been obtained above the F2 peak; and these extend to less than 1000 kilometers, while the higher altitude region is still virtually unexplored. However, ionosphere rocket measurements to well beyond 1000 kilometers are planned for the near future.

This report shows the potential importance of high altitude electron density measurements in inferring the structural parameters of the earth's outer atmosphere.

ALTITUDE DISTRIBUTION OF IONS IN DIFFUSIVE EQUILIBRIUM

It is generally agreed that the distribution of electrons and ions at altitudes well above the F2 peak should be in diffusive equilibrium. Although in a neutral atmosphere each constituent in diffusive equilibrium is distributed independently of the others, Mange pointed out (Reference 1) that in a heterogeneous ionosphere the distribution of an ionic species (especially a light one) is influenced by the presence of the others because of the electric field resulting from the slight charge separation between electrons and positive ions.

† The previous release of this report bore the same title but was identified as Technical Note D-1065.

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In general, the distribution with height of an ionic constituent in diffusive equilibrium can be written as

$$n_i = n_{io} \exp\left[-\int_o^z \frac{\left(m_i - \frac{m_+}{2}\right) g}{kT} \, dz\right] \tag{1}$$

where n_i is the number density, m_i is the mass of the i^{th} ionic constituent, $m_+ = \sum_i n_i m_i / \sum_i n_i$ is the mean ionic mass, g is the acceleration of gravity, k is the Boltzmann constant, T is the absolute temperature, and $z = h - h_o$ is a height parameter measured with respect to a reference level h_o.

ELECTRON DENSITY DISTRIBUTION IN A HETEROGENEOUS UPPER IONOSPHERE

Because of charge neutrality (i.e., the number density of electrons equals the total number density of positive ions: $N = \sum_i n_i$) the electrons are distributed according to a hypothetical species having the mean ionic mass m_+. Thus, according to Equation 1 the electron density distribution is given by

$$N = N_o \exp\left[-\int_o^z \frac{g m_+}{2kT} \, dz\right] . \tag{2}$$

The same distribution is obtained by simply assuming that ambipolar diffusion is the predominant process affecting the electron density distribution above the F2 peak.

Computations by Shimazaki (Reference 2) show that diffusive equilibrium is established very quickly above 300 kilometers. There is also recent experimental evidence (References 3 and 4) to indicate a diffusive equilibrium distribution of the electrons and ions above the F2 peak.

The condition for diffusive equilibrium of the electron-ion gas is given by

$$\operatorname{div} (N \vec{V}_D) = 0 \cdot \tag{3}$$

In an isothermal atmosphere, at middle latitudes (where ambipolar diffusion is affected only slightly by the earth's magnetic field) the diffusion velocity V_D is assumed to be acting mainly in the vertical (z) direction as the result of gravity and is given by

$$V_D = -D_a \left[\frac{1}{N} \frac{\partial N}{\partial z} + \frac{m'}{m} \frac{1}{H}\right] \tag{4}$$

where D_a is the ambipolar diffusion coefficient which is directly proportional to $\sin^2 I$ (I = magnetic dip) and inversely proportional to the atmospheric gas density, m is the mean molecular mass of the atmospheric gas within which the charged particles diffuse, and $H = kT/mg$ is the neutral scale height.

The effective mass of the electron-ion gas is, in general, given by

$$m' = \frac{m_+ T_i}{(T_i + T_e)}$$

where T_i and T_e are the ion and electron temperatures, respectively.

For local thermodynamic equilibrium

$$m' = \frac{m_+}{2} \quad .$$

Evaluating the condition given by Equation 3 by using Equation 4 we obtain as one solution

$$\frac{1}{N} \frac{\partial N}{\partial z} = \frac{-m'}{m} \frac{1}{H} = \frac{-gm_+}{2kT} \tag{5}$$

which, after integration, is identical to Equation 2. The term $gm_+/2kT$ corresponds to the reciprocal of the scale height of the electron ion gas H'. This solution is equivalent to

$$V_D = 0 \quad .$$

The second solution yields

$$\frac{1}{N} \frac{\partial N}{\partial z} = \frac{-1}{H} \quad .$$

This corresponds to a finite diffusion velocity ($V_D > 0$) leading to an outflow of charged particles to a sink at extreme altitudes. For this reason this solution cannot be accepted as a true equilibrium condition.

We shall now consider the electron density distribution well above the F2 peak in an ionosphere consisting of a binary ion mixture (O^+ and H^+, or O^+ and He^+). According to satellite measurements (Reference 5), O^+ is the predominant heavy ion in the upper ionosphere. At greater altitudes the protons resulting from the telluric hydrogen corona should become predominant (Reference 6). Recently, Nicolet (Reference 7) has pointed out that the hydrogen concentrations would have to be unacceptably high to explain the decrease of mean molecular mass above 750 km that is required for an isothermal atmosphere based on satellite density data. For this reason he suggests that He and He^+ may play an important role in this high altitude region.

The mean ionic mass in an isothermal ionosphere consisting of a binary ion mixture is given by

$$m_+ = \frac{m_1 + m_2 \eta \exp(Kz)}{1 + \eta \exp(Kz)} \tag{6}$$

where m_1 is the mass of the heavy ionic constituent (O^+) and m_2 is the mass of the light ionic constituent (H^+ or He^+). Also, $\eta = n_2/n_1$ at the reference level ($z = 0$), where n_1 and n_2 are the concentrations of the heavy (O^+) and light (H^+, He^+) ionic constituents, respectively, and $K = (m_1 - m_2)g/kT$. It is easily shown that

$$\int_0^z m_+ dz = \frac{1}{K}\left\{(m_2 - m_1)\left[\ln\left(1 + \eta \exp(Kz)\right) - \ln(1 + \eta)\right] + m_1 Kz\right\}. \tag{7}$$

Since $\ln(1 + \eta)$ will be negligibly small, substituting Equation 7 into Equation 2 we obtain the following expression for the electron density distribution.

$$N = N_o \exp\left\{\frac{1}{2}\left[\ln\left(1 + \eta \exp\left(\frac{z}{H_{12}}\right)\right) - \frac{z}{H_1}\right]\right\} \tag{8}$$

where $H_1 = kT/m_1 g$ and $H_{12} = kT/(m_1 - m_2)g$.

Because of the variation of g with altitude, H_1 and H_{12} will not be constant although the temperature is constant. However, if the height parameter z is expressed in terms of the modified geopotential altitude given approximately by

$$h' = \frac{R_o h}{R_o + h}$$

where R_o is the earth's radius, g can be replaced by g_o (acceleration at the earth's surface) and the scale heights H_1 and H_{12} are then constants.

It should be noted that at great altitudes (above 3000 kilometers) Equation 8 is not strictly applicable because it neglects the effects of the earth's rotation. At these altitudes the accurate geopotential altitude (instead of the approximation given above) must be used as the height parameter.

Figure 1 shows relative electron density profiles computed by means of Equation 8 for a temperature of $T = 1500°K$ and parametric values of the relative concentration of light to heavy ions (η) at the reference level h_o. This reference level may be chosen to be located about two or three (neutral) scale-heights above the F2 peak, say at an altitude of 500 km.

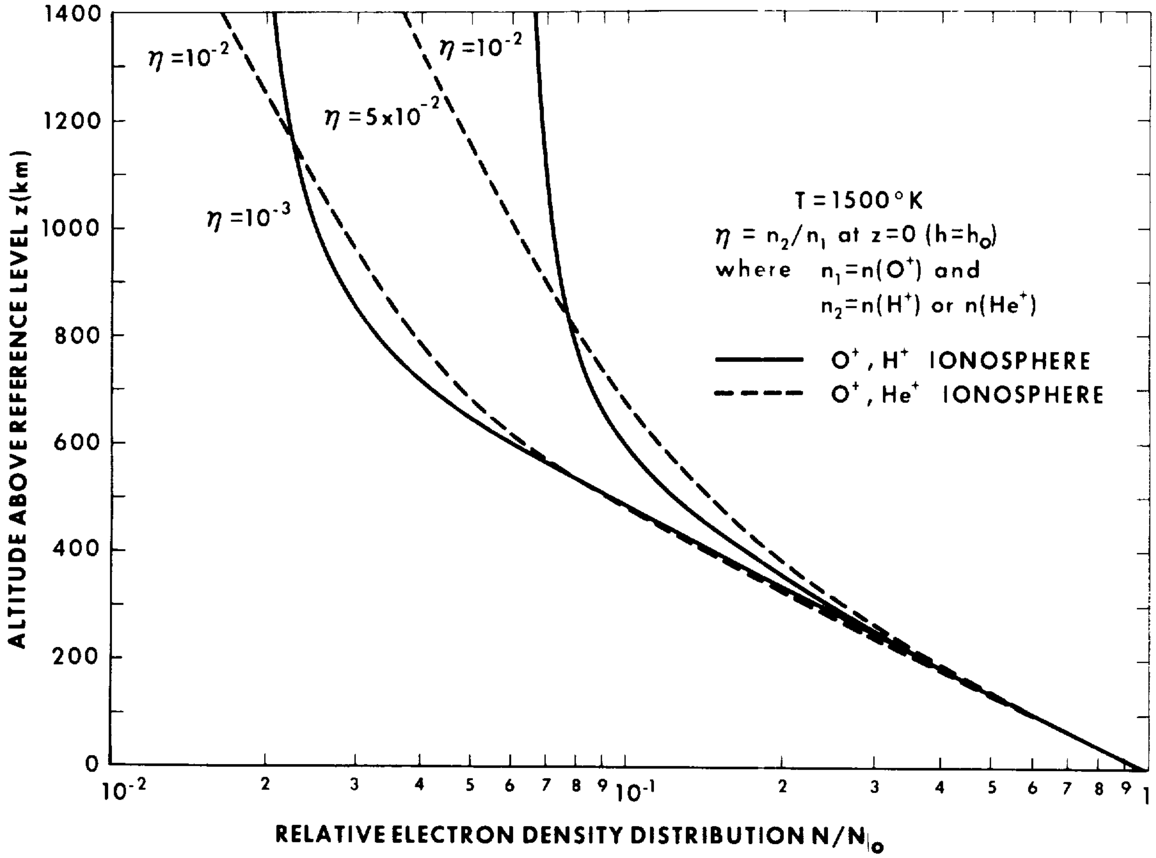

Figure 1 - Relative electron density distribution in an isothermal upper ionosphere consisting of a binary ion mixture (O^+, H^+ or O^+, He^+)

The relative profile corresponding to an O^+, H^+ ionosphere with $\eta = 10^{-2}$ at h_o is most likely an upper limit because of the high hydrogen concentration required for such a ratio η. The concentration ratios (η) for the O^+, He^+ ionosphere are representative of the helium concentration suggested by Nicolet (Reference 7).

CONCLUSION

It is obvious that from a measured electron density profile well above the F2 peak a number of atmospheric parameters can be deduced: From the slope of the electron-density distribution, the scale height of the electron-ion gas, and the portion of the profile where either the heavy ion O^+ or the light ions H^+ and He^+ predominate, the temperature can be determined. Such temperature determinations have already been made for the region where O^+ is the predominant ion (References 3 and 4).

An electron density profile measured with an accuracy of a few percent would, for example, also allow us to differentiate between an O^+, H^+ ionosphere with $\eta = 10^{-3}$ and an O^+, He^+ ionosphere with $\eta = 10^{-2}$ (Figure 1) and provide an estimate of the concentration of the light ion.

In this report the most simple case of a binary-ion mixture where the light ionic constituent is either hydrogen or helium has been used. Although the actual case may well be more complex, the simple model distributions discussed here may serve as guide lines in the interpretation of the electron density distribution in the region of the upper atmosphere wherein a transition occurs from the predominant heavy ion (O^+) to the light ions (H^+ and/or He^+).

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